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**REVIEW ARTICLE**

**The Scope of 4D Printing in Endodontics**

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**Abstract**

Three-dimensional printing has revolutionized modern dentistry by enabling personalized, digitally driven procedures. However, its static constructs fail to mimic the dynamic behavior of oral tissues. Four-dimensional printing—an evolution of 3D technology—introduces time-responsive smart materials that can change shape or function in response to external stimuli. This narrative review explores the progression from three-dimensional to four-dimensional printing, highlighting the potential applications of 4D technology in endodontics. Emphasis is placed on how four-dimensional printing may address current limitations in regenerative endodontic scaffolds, intracanal drug delivery, and adaptive obturation systems. Given the lack of direct clinical implementation, this review outlines the theoretical and experimental scope of 4D printing in endodontics.

**Keywords:** 3D printing, 4D printing, Dentistry, smart materials, shape memory polymers, regenerative dentistry

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### **Introduction: The Rise of Additive Manufacturing in Dentistry**

The three-dimensional (3D) printing has played a pivotal role in various dimensions of dentistry, such as preparation of surgical guides, rapid and accurate fabrication of prosthesis and modification of various devices, etc. [1,2]. It has also been used in endodontics mainly for the development of customized guides for doing access cavity preparation in calcified canals, for making training models, and for modifying and optimizing scaffolds for regenerative endodontics [3]. Nevertheless, despite these advances, this technique has not been able to be explored to its full potential in endodontics. This is primarily because 3D printing cannot maintain the dynamism in its output, resulting in static outcomes. There is no possibility of changing or adapting the geometry and configuration of the output after printing [4]. Furthermore, the regenerative capability of static scaffolds is limited because they are not able to adjust to changing internal anatomy or healing environments [5]. These drawbacks highlight the need for a technology that can capable of producing biomimetic, dynamic, and stimulus-responsive structures.

### **4D Printing: Evolution and Definition**

The concept of four-dimensional (4D) printing was first presented by Skylar Tibbitts at MIT in 2013. He defined it as 3D printing that has been improved with smart materials that allow

for gradual change in shape or property over time [6]. Time, the fourth dimension, makes the structures dynamic and functionally adaptive by allowing them to react to stimuli such as heat, moisture, pH, or magnetic fields [7]. In contrast to 3D models, 4D printed devices can transform after printing, offering real-time interaction with biological environments [8].

### **Materials and Mechanisms of 4D Printing**

Various smart materials have been used in 4D printing, such as shape-memory polymers (SMPs), hydrogels, and composites, sensitive to various stimuli [9]. When heated, SMPs can return to a predefined form, making them suitable for space-adapting scaffolds and root canal obturation [10]. Hydrogels have superior biocompatibility and tunable properties, which make them suitable for dental applications, especially in regenerative endodontic strategies [11]. These materials are printed using advanced stereolithography systems or multi-material extrusion, making them capable of creating structures with integrated functionality. However, there are certain limitations to using hydrogels and shape-memory polymers in dentistry. Hydrogels often lack mechanical strength and tend to lose their effectiveness over time as they swell and shrink repeatedly. Shape-memory polymers also respond to changes in temperature, but they may go back to their original shape too quickly or in an unexpected way, which can make them

less useful in complicated clinical situations [6].

### **Applications of 4D Printing in Dentistry**

4D printing in dentistry is currently utilized for corroborative tasks in creating self-adjusting orthodontic aligners, smart implants, adaptive prosthesis, and consumptive drug-releasing devices [5,9]. In periodontics, smart scaffolds are emerging for tissue regeneration under biomechanical load [12]. In Prosthodontics, removable dentures are developed to adapt to mucosal changes, and dynamic implants that integrate better with bone are studied in oral surgery [13]. Even though most of these applications are at an experimental stage, they are advanced steps toward a dynamic and personalized form of dentistry.

### **Potential Applications in Endodontics**

Despite a lack of direct research on 4D printing in endodontics, its potential is vast. Smart scaffolds made with 4D technology could release therapeutic agents in response to inflammation or infection, improve healing through programmed degradation, and be able to adjust to irregular root canal anatomy [10,11]. The major application of 4D in endodontics can be in the form of root canal fillings, which can better adapt to irregularities of the root canal by changing the shape after insertion. This increases the chance of root canal sealing in all dimensions, which will further reduce the chance of

treatment failure by bacterial leakage. Shape-memory obturation materials may improve canal sealing by extending into small lateral canals when heated [7]. To improve treatment outcomes, future systems might incorporate intelligent intracanal drug delivery platforms that release medication in response to microbial activity.

### **Limitations and Future Scope**

High fabrication costs, limited clinical-grade smart materials, and lack of data on long-term biocompatibility present difficulties for 4D printing despite its transformative potential [14]. Printing resolution and response predictability are still major technical challenges. More in vitro and in vivo studies are needed in endodontics to validate mechanical performance, therapeutic impact, and material safety. As interdisciplinary research progresses, the integration of artificial intelligence with 4D printing may further enhance material responsiveness and procedural customization.

### **Conclusion**

4D printing brings intelligent, dynamic, responsive constructions to dentistry. Although its application in endodontics is still hypothetical, its capacity to overcome important constraints of 3D-printed systems makes it a future tool of promise. 4D printing is expected to revolutionize regenerative endodontics, drug delivery, and biomaterial-based therapies as studies on dental smart materials expand.

## Statements and Declarations

### Conflicts of interest

The authors declare that they do not have conflict of interest.

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